Development of a Novel Ceramic-to-Metal Seal for High-Temperature, High-Pressure Applications

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Patcharin N. Burke, Project Manager

Outline

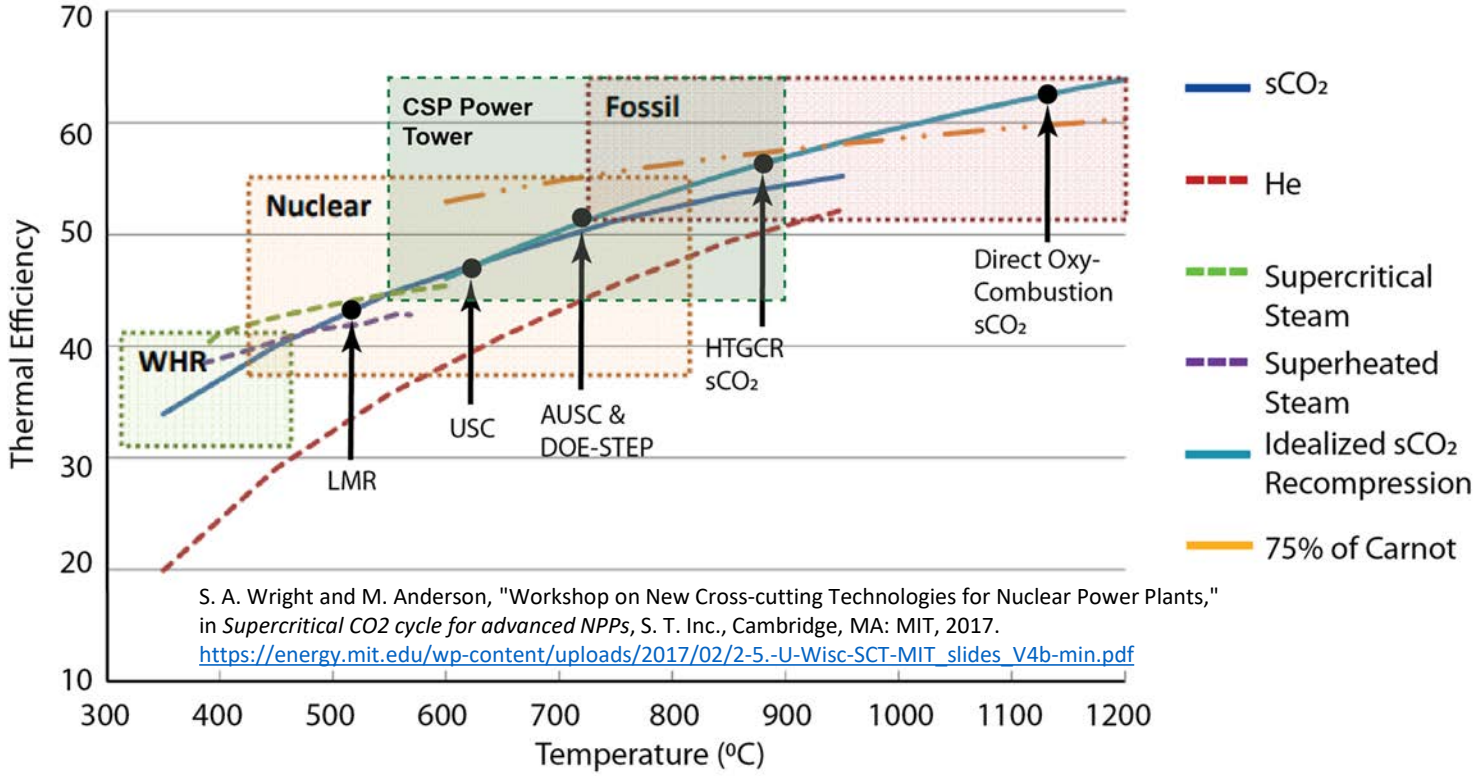
- Technical challenge: High-T, High-P ceramic-to-metal seals
- Solution: Cermet-filled U-ring seal design concept
- Seal performance goal: 800°C, 100 cycles, 3000 psi
- Experimental
- Results for Ag at 700 °C and AgPd U-rings at 750 °C
- Failure analyses (FA)
- FEA modeling for FA, seal design, and process optimization
- High-T, High-P seal applications and voice of customer
- Summary and Future Efforts

New High-Temperature, High-Pressure Seals Needed

- Reliable high-temperature seals of metal pipes to ceramic heat exchangers are required
- Enables advanced high-temperature power generation systems that utilize power cycles based on steam or supercritical CO_2 (sCO_2)

Lewinsohn, Charles. "High-efficiency, ceramic microchannel heat exchangers." Bull. Am. Ceram. Soc. 94, no. 5 (2015): 26-31.

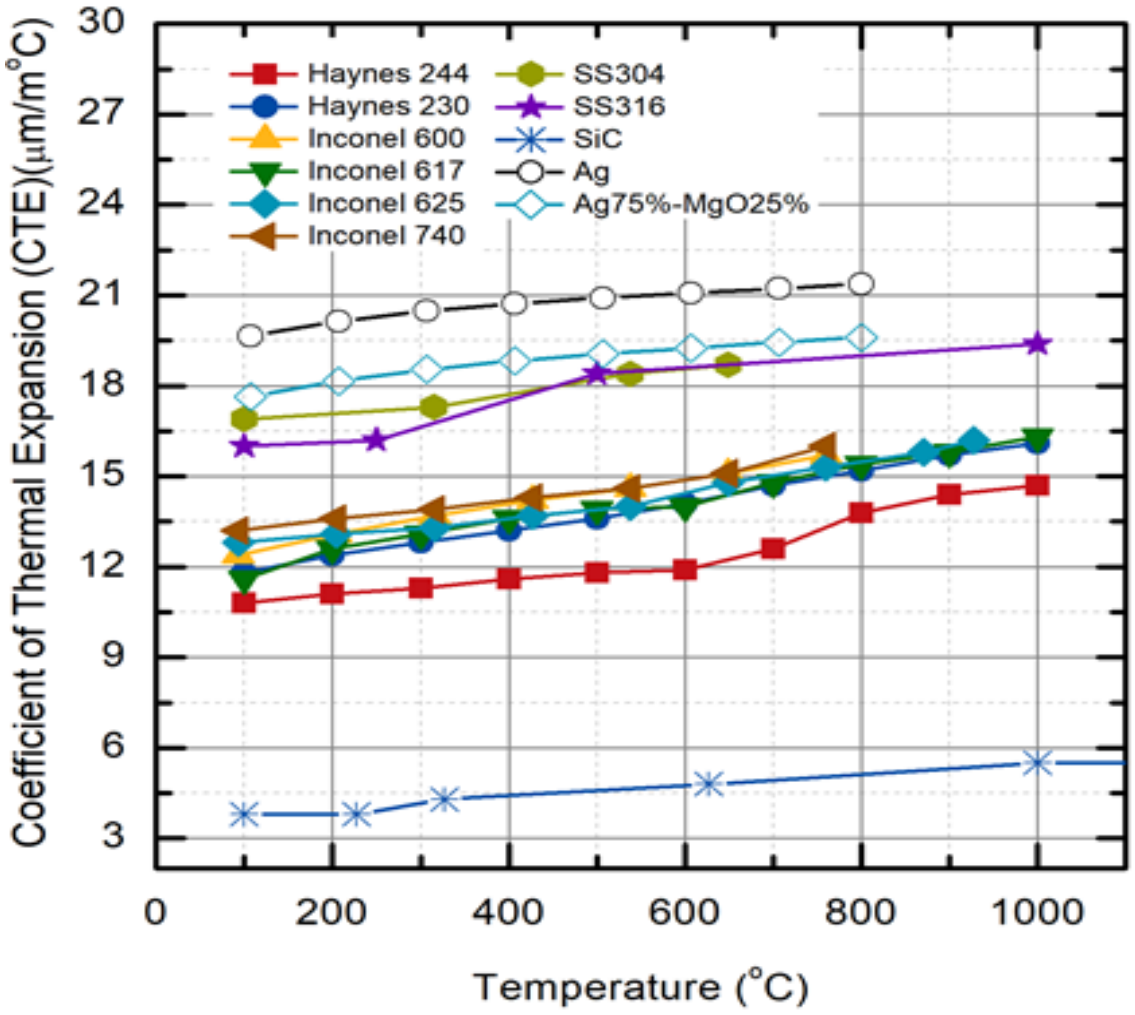
Lewinsohn, Charles A., Merrill A. Wilson, Joseph R. Fellows, and Hyrum S. Anderson. "Fabrication and joining of ceramic compact heat exchangers for process integration." International Journal of Applied Ceramic Technology 9, no. 4 (2012): 700-711.



S. A. Wright and M. Anderson, "Workshop on New Cross-cutting Technologies for Nuclear Power Plants," in *Supercritical CO2 cycle for advanced NPPs*, S. T. Inc., Cambridge, MA: MIT, 2017. https://energy.mit.edu/wp-content/uploads/2017/02/2-5.-U-Wisc-SCT-MIT_slides_V4b-min.pdf

High-Temperature, High-Pressure Seal Challenge

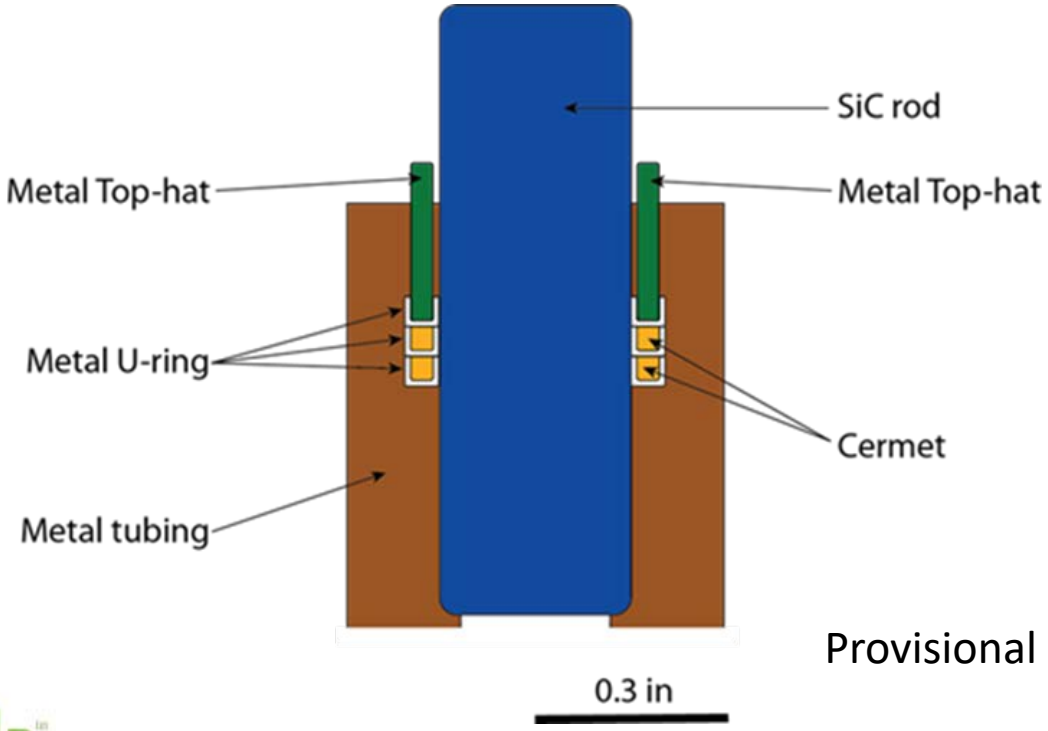
- CTE mismatch between SiC/Si_3N_4 and metals creates challenges for sealing
- Cermet-filled U-Ring seal formed in situ provides solution



[1] BSU measured the CTE of SiC, Ag, and Ag75%-MgO25%

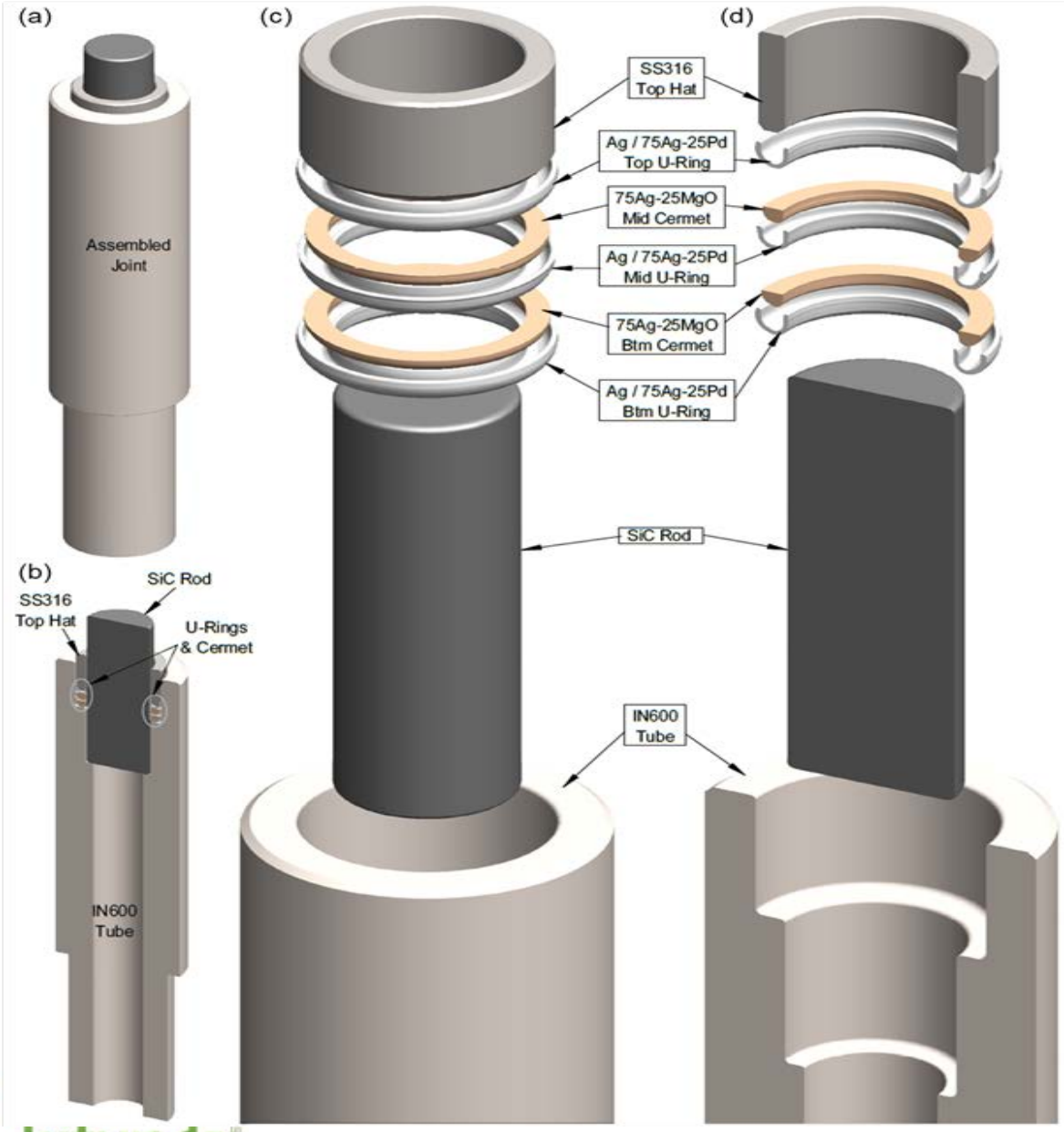
Technical Approach

- Cermet-filled U-Ring seal assembly formed in situ at high temperature (maximum gap)
- CTE of cermet powder (Ag/MgO) is higher than SiC or IN600 that are being joined together
- Cermet-filled U-Ring seals are plastically deforming during hot seal forming process
- Seals fill the gap between a metal tube and ceramic rod (tube)
- MgO component of cermet provides stability and strength at high T and P
- Maintains high-pressure gas-tight seal during thermal cycling

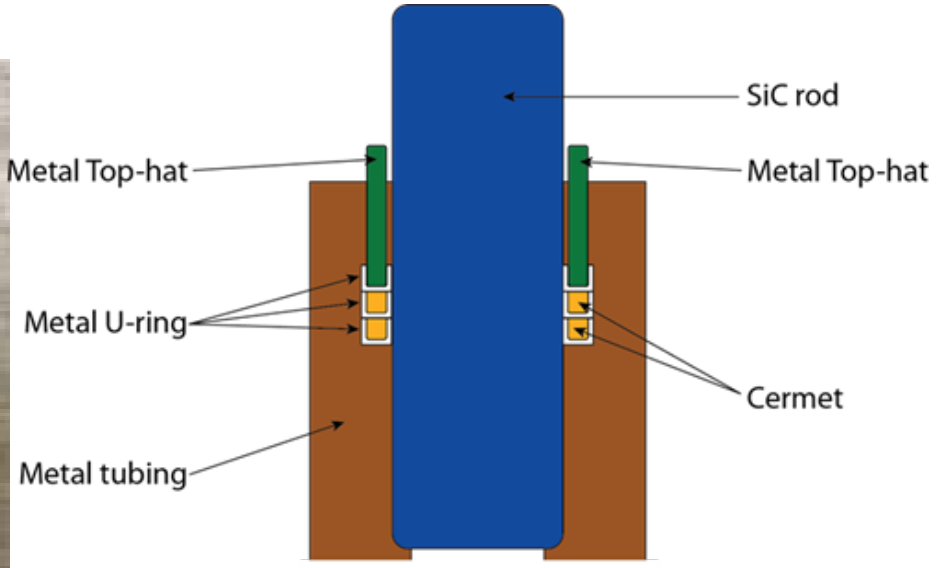


Provisional Patent: 62/728,449

Cermet-Filled U-Ring Seal Design



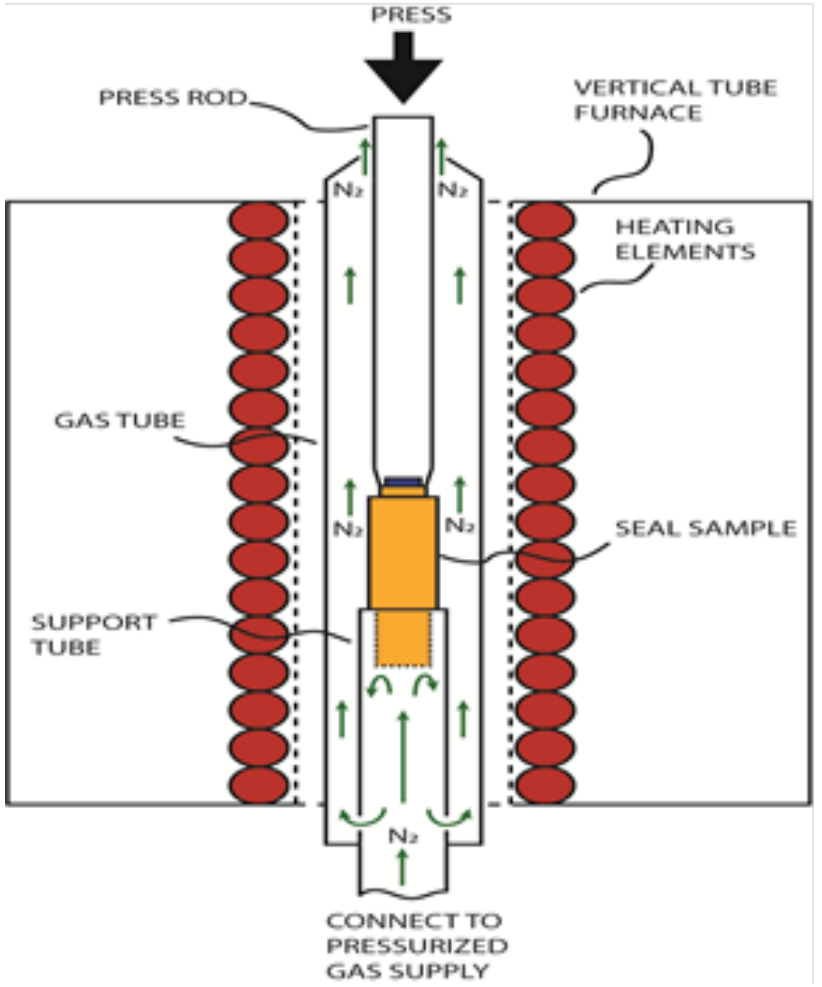
Seal test sample



U-Ring (ID=0.315”)

Hot Seal Forming Apparatus

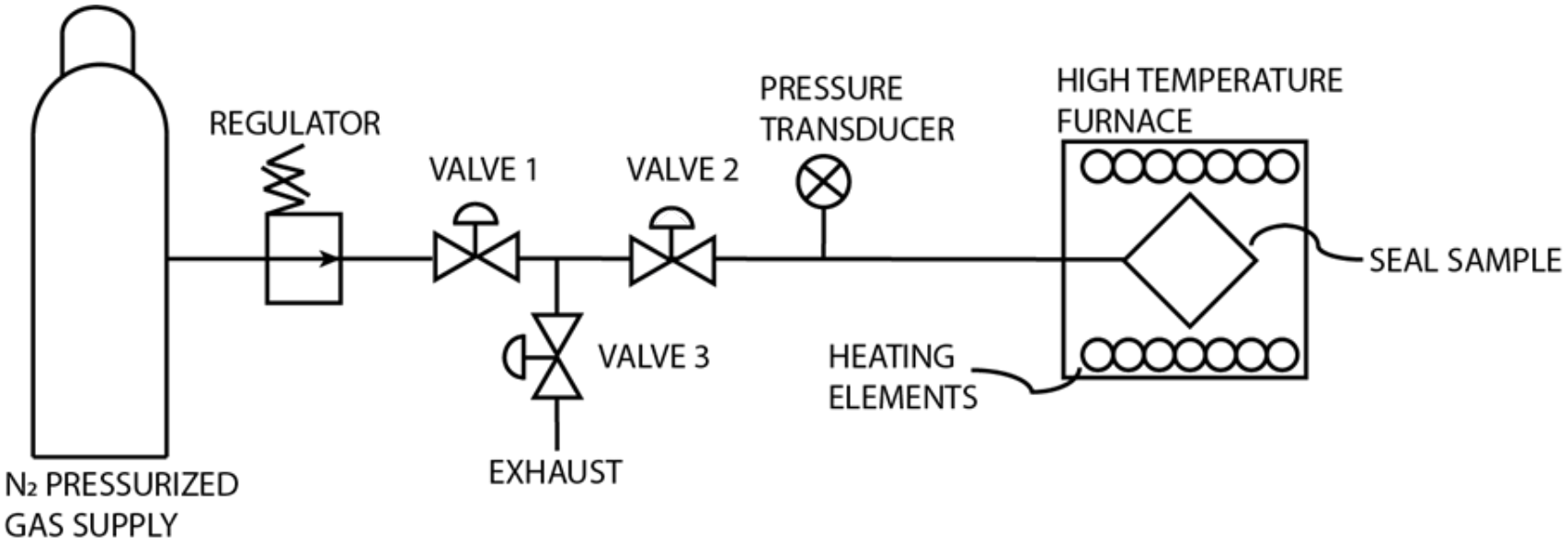
Hot hydraulic press

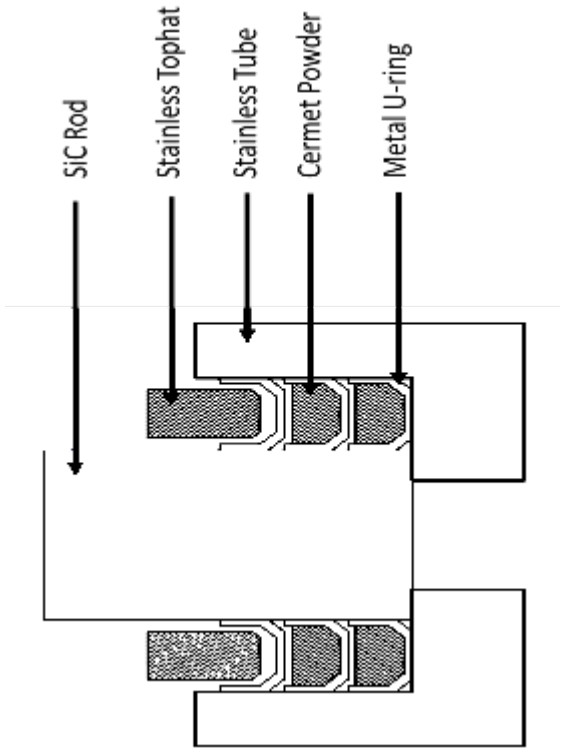


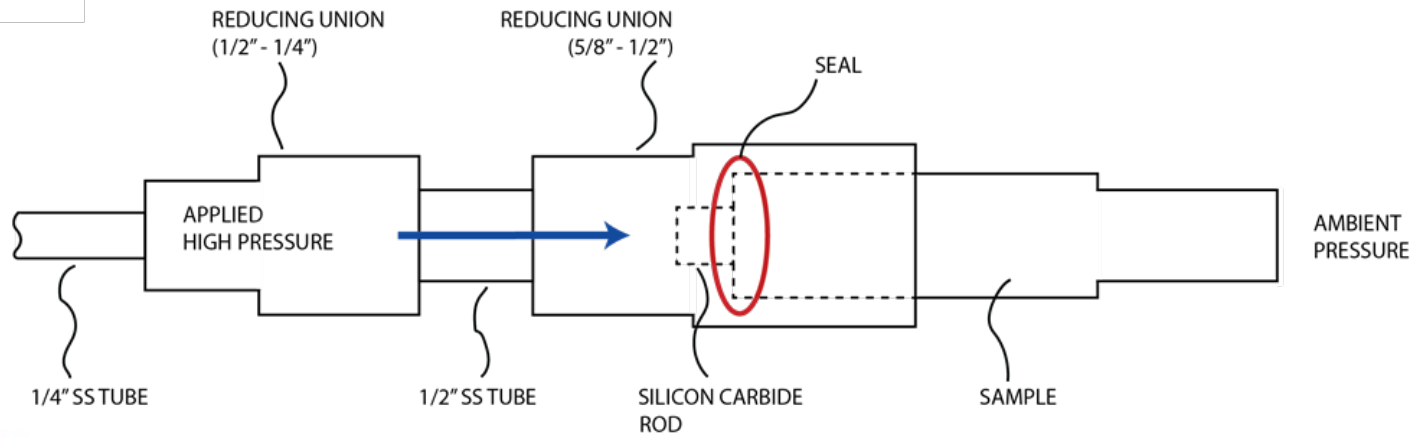
System schematic

- Seals are assembled and then pressed under N_2 at 900°C and 13,700 psi
- For testing, seals are cycled between atmospheric conditions and high pressure (3000 psi) and high temperature (700-800°C)
- Pressure decay shows seal performance
- After testing, samples are x-ray imaged, cross-sectioned, and characterized

High Temperature and Pressure Leak Test Rig

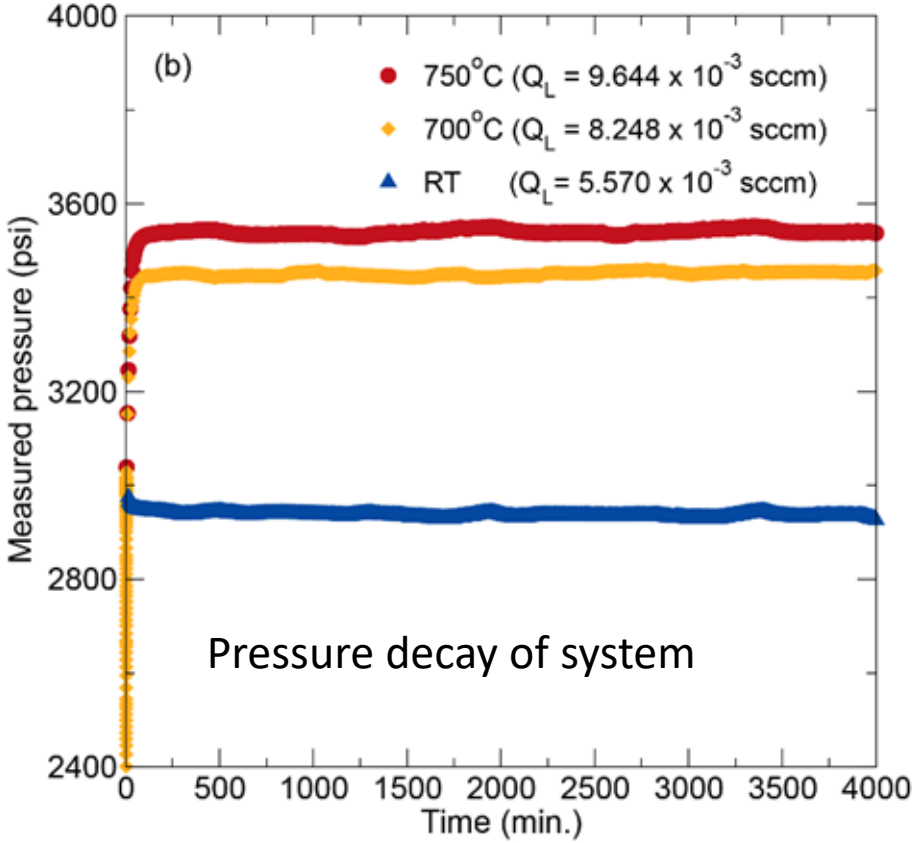


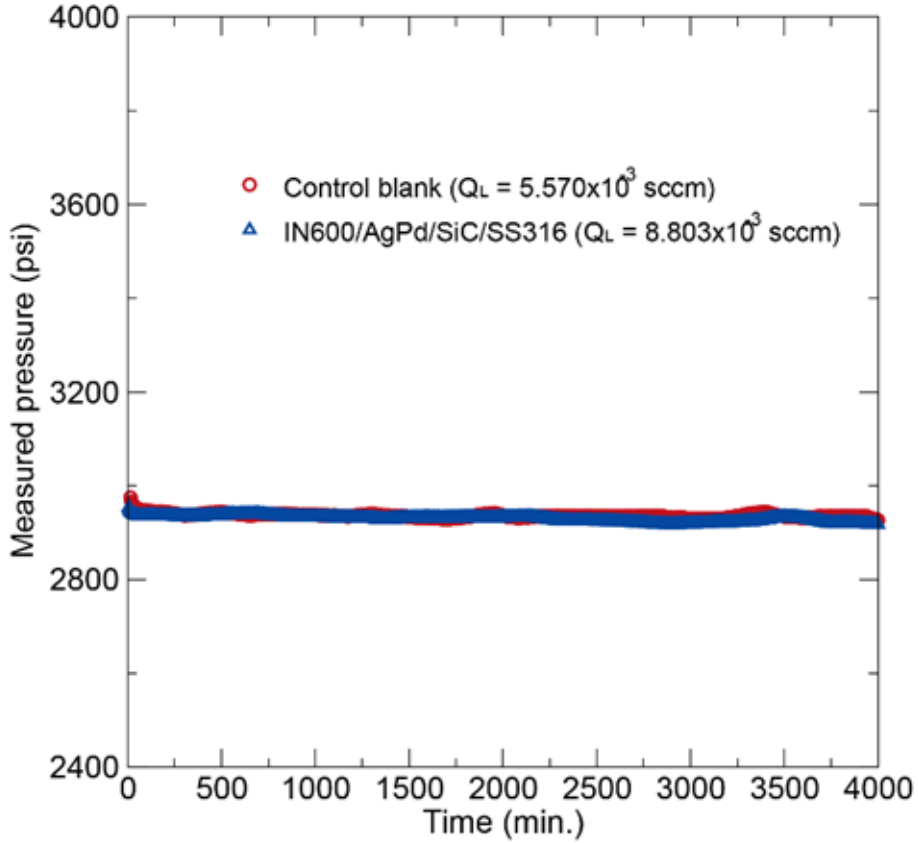




High Temperature and Pressure Leak Test Rig Capability

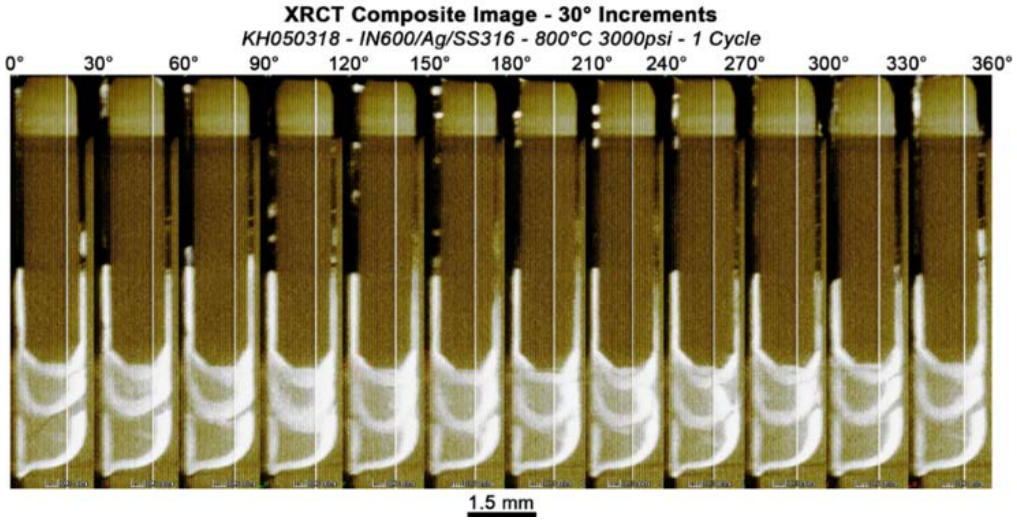
- Pressure decay leak measurement system is capable of detecting small leaks (<0.01 sccm) at elevated temperatures and pressures
- Trade-off between measurement time and leak rate measurement accuracy



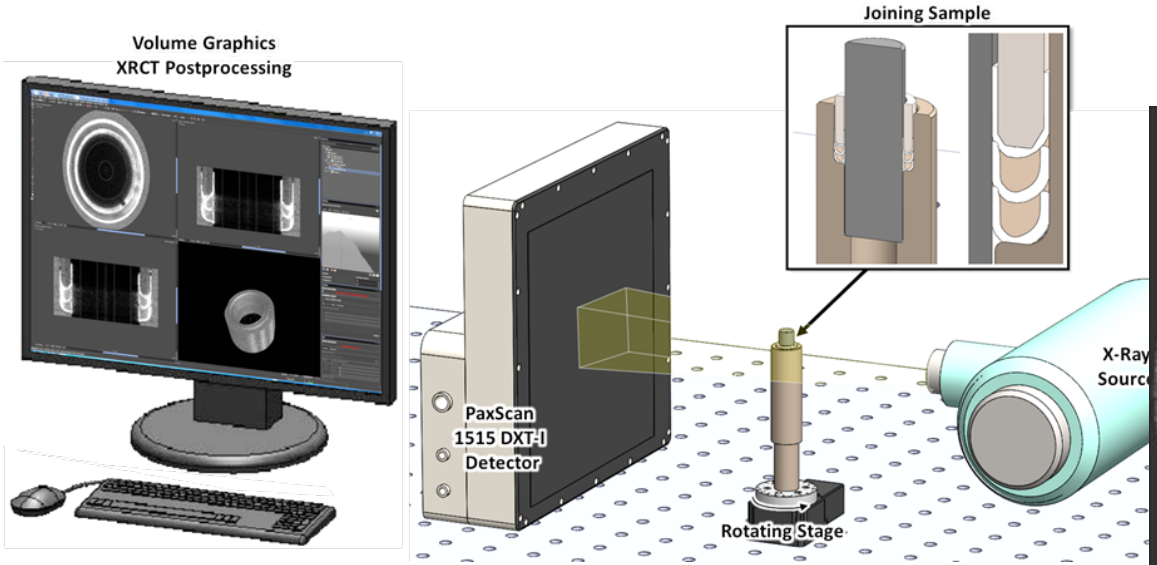


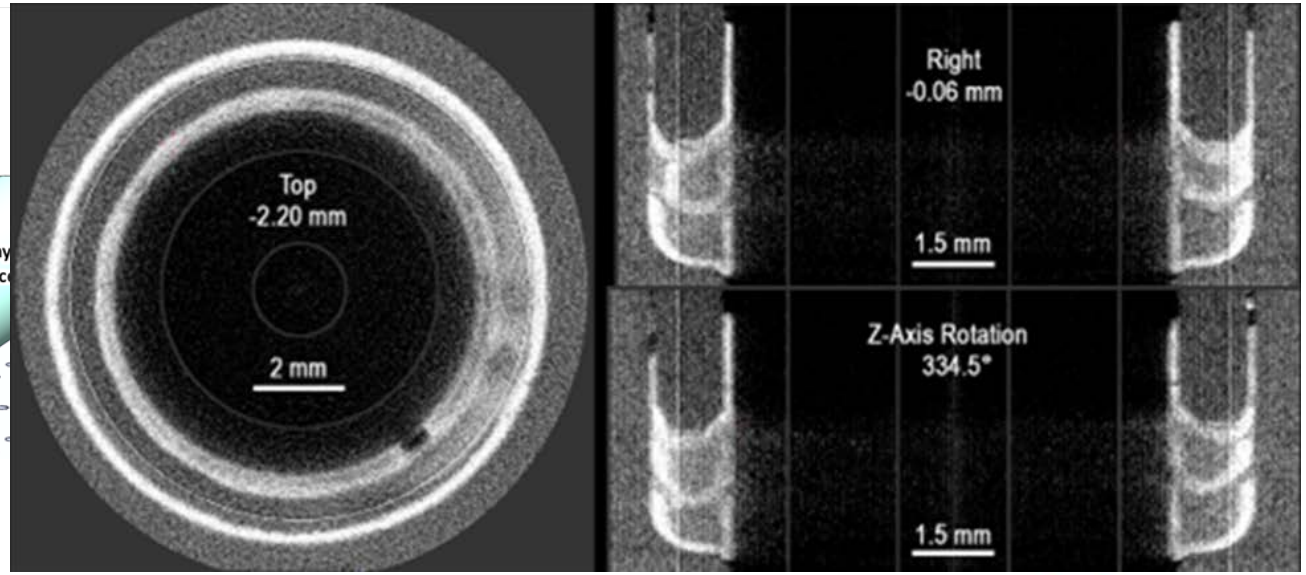
Seal Failure Analyses: X-Ray Computed Tomography (XRCT)

- Collaborating with INL[1] to perform XRCT scans of failed and control seal assemblies
- XRCT to nondestructively observe seals
- Cross section at specific locations to better understand chemistry and microstructure



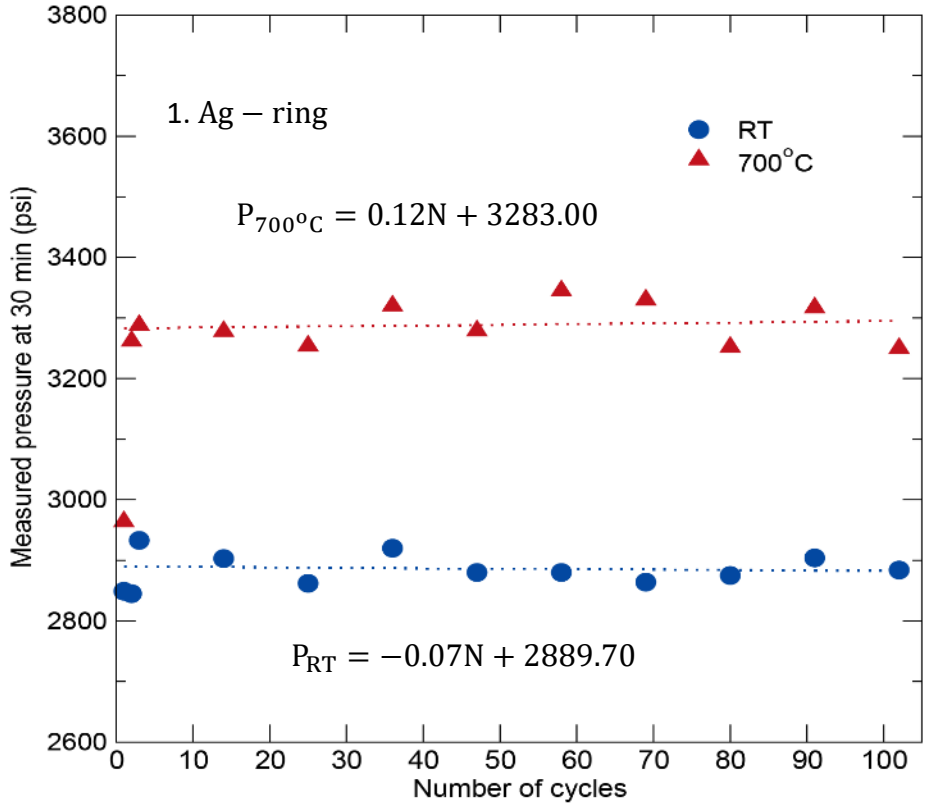
XRCT Characterization Overview Schematic

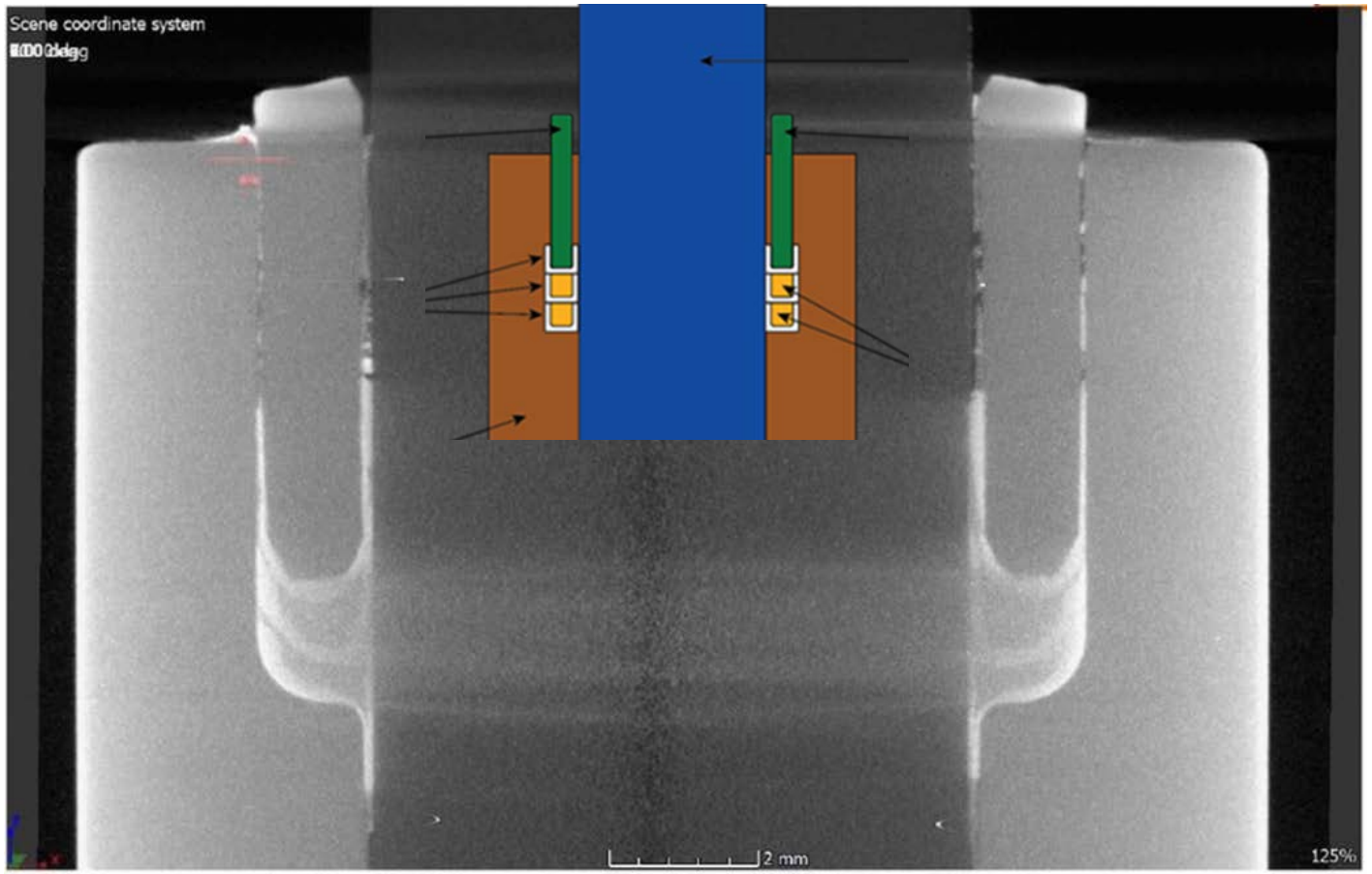




1. Richard Skifton at Idaho National Laboratory (INL)

Performance of Ag U-Ring Seal Assembly at High T and P

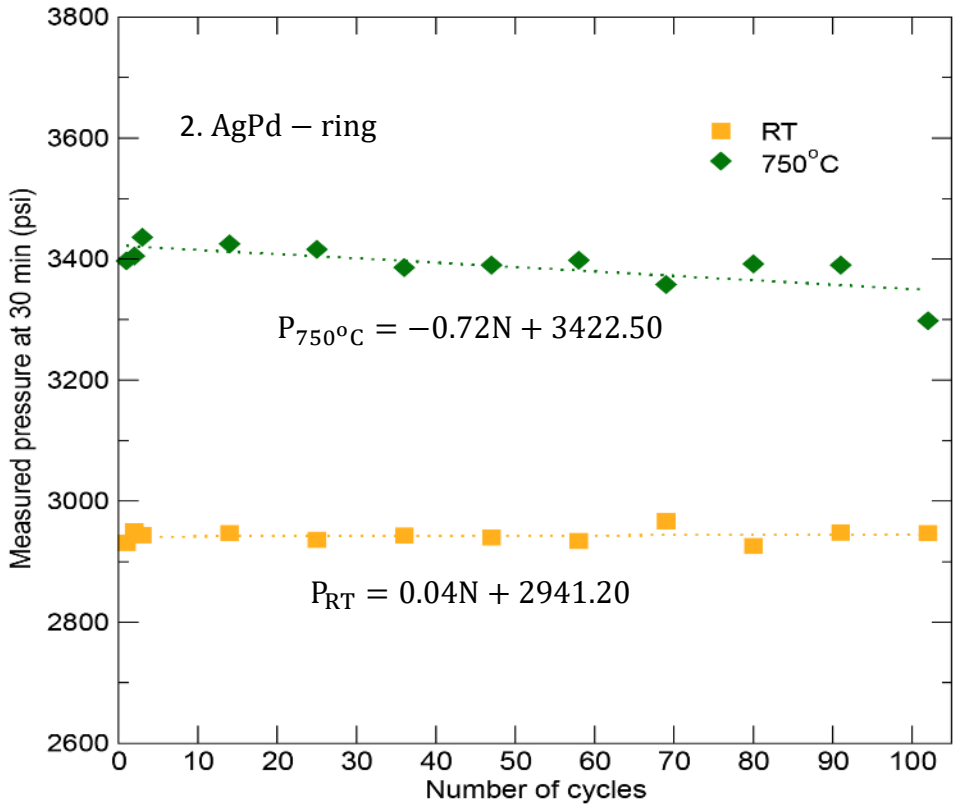


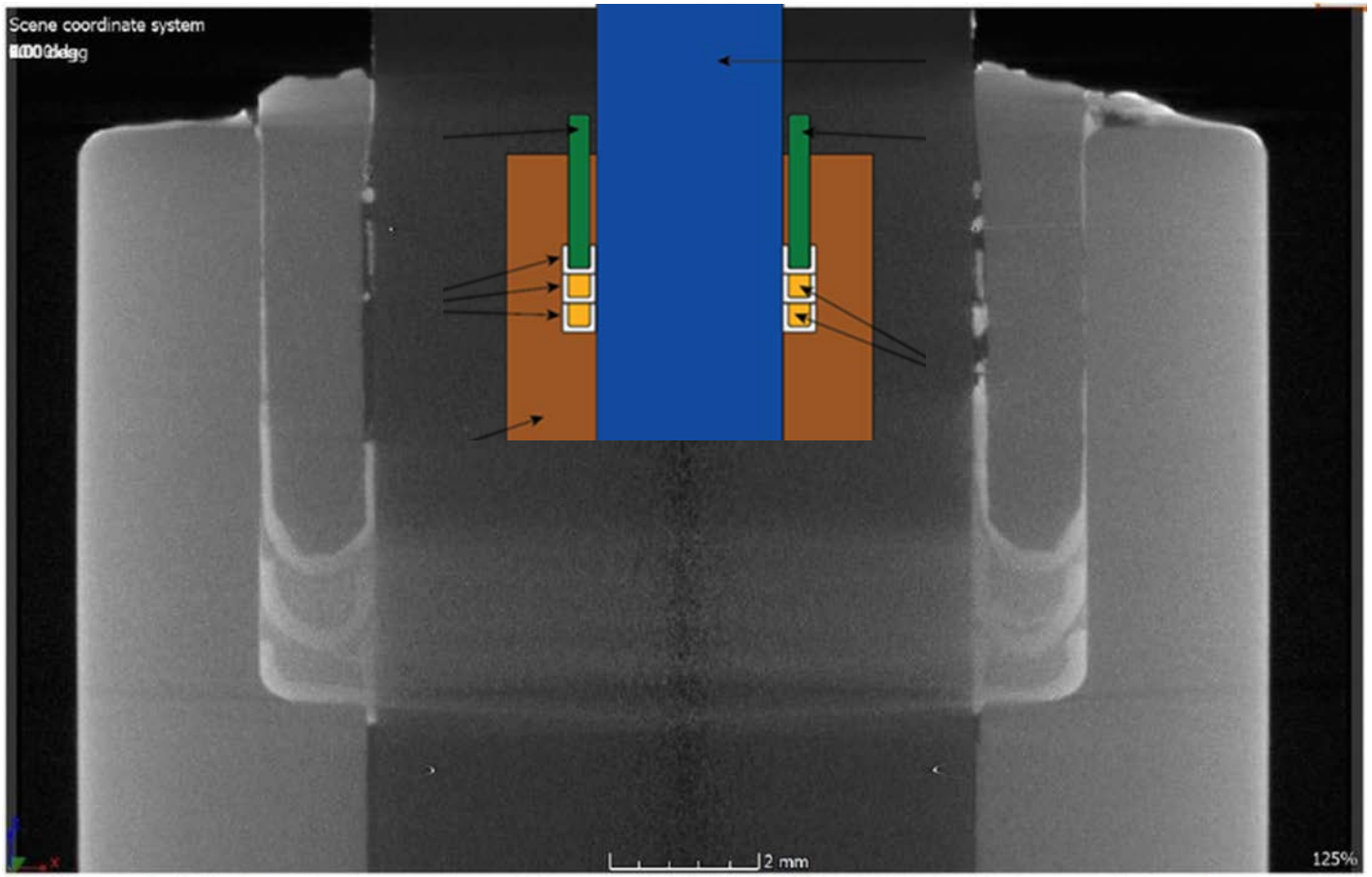


No.	Name	Tube	U-ring	Cermet	Ink
1	KH041018JOIN	Inconel 600	Ag	Ag75-MgO25	Ag
2	KH061318JOIN	Inconel 600	Ag75-Pd25	Ag75-MgO25	Ag

P = measured pressure (psi)
N = number of cycles

Performance of AgPd U-Ring Seal Assembly at High T and P





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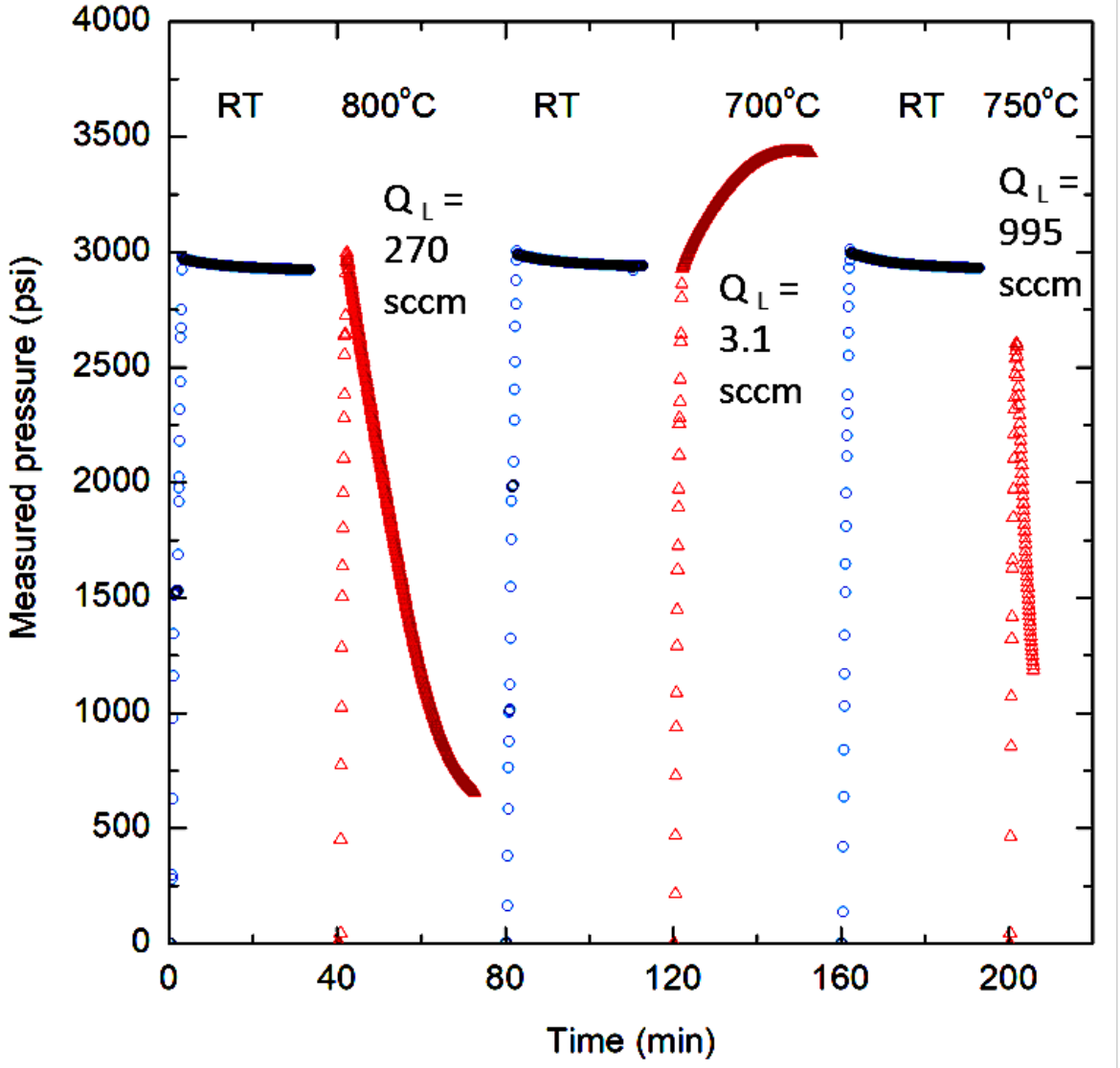
1	KH041018JOIN	Inconel 600	Ag	Ag75-MgO25	Ag
2	KH061318JOIN	Inconel 600	Ag75-Pd25	Ag75-MgO25	Ag

P = measured pressure (psi)
N = number of cycles

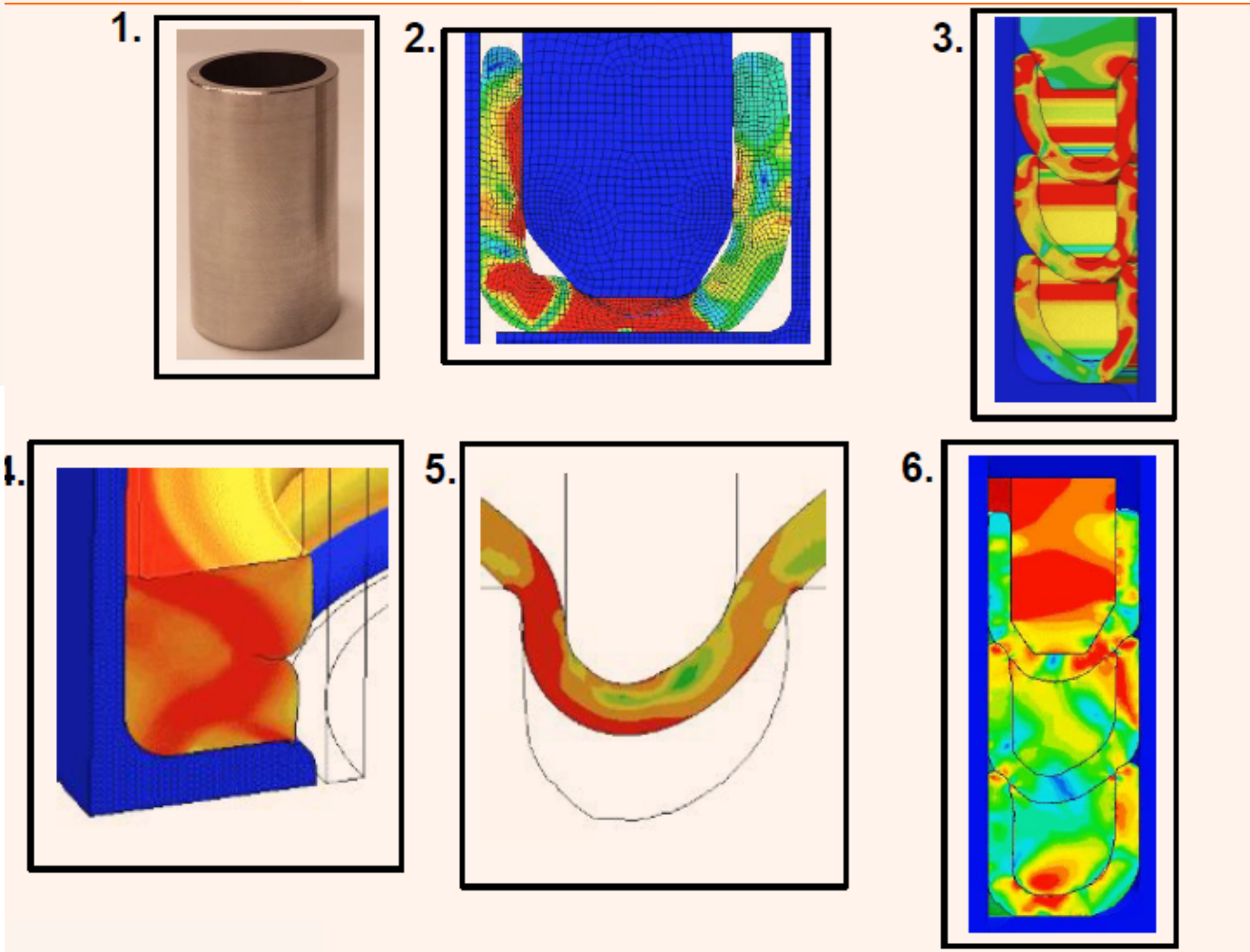
U-Ring Seal Assembly Performance at Higher Temperatures

- Ag U-Ring seal assembly leaked after single exposure to 760°C
- Ag (75%)-Pd (25%) alloy (AgPd) U-Ring performed well for >80 cycles at 750°C
- AgPd seal assembly failed after 1st thermal cycle to 800 °C



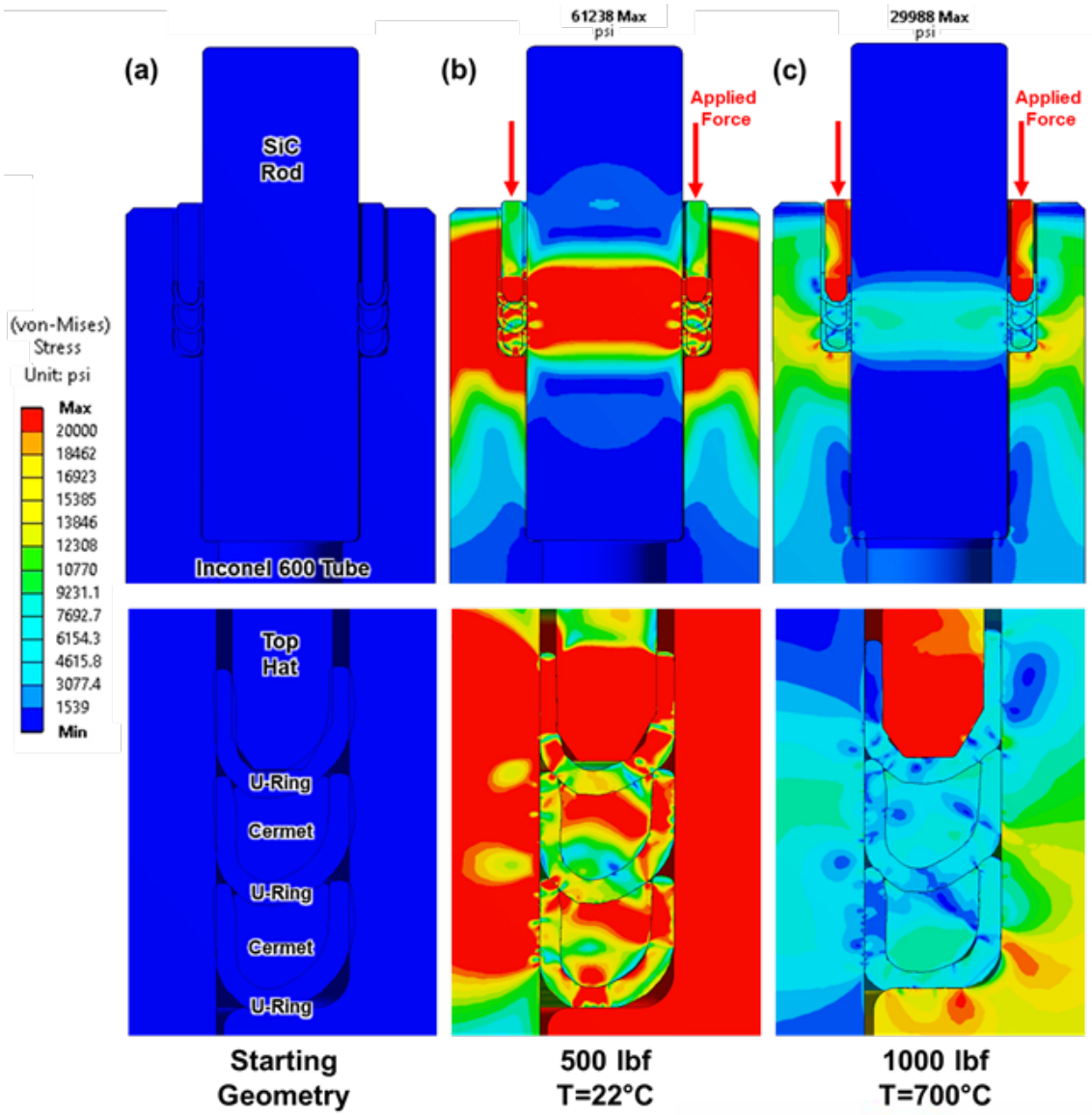
FEA Modeling

- CAD and FEA modeling are used extensively on project to support multiple activities
  - Failure analyses and XRCT images
  - Tolerance stackup analyses
  - Hot seal forming simulation
    - Single U-Ring + top hat (2)
    - 3 U-rings + top hat (3)
    - Cermet compression (4)
    - Complete seal assembly (6)
  - U ring forming from Ag sheet stock (5)
  - Evaluation of alternate seal designs



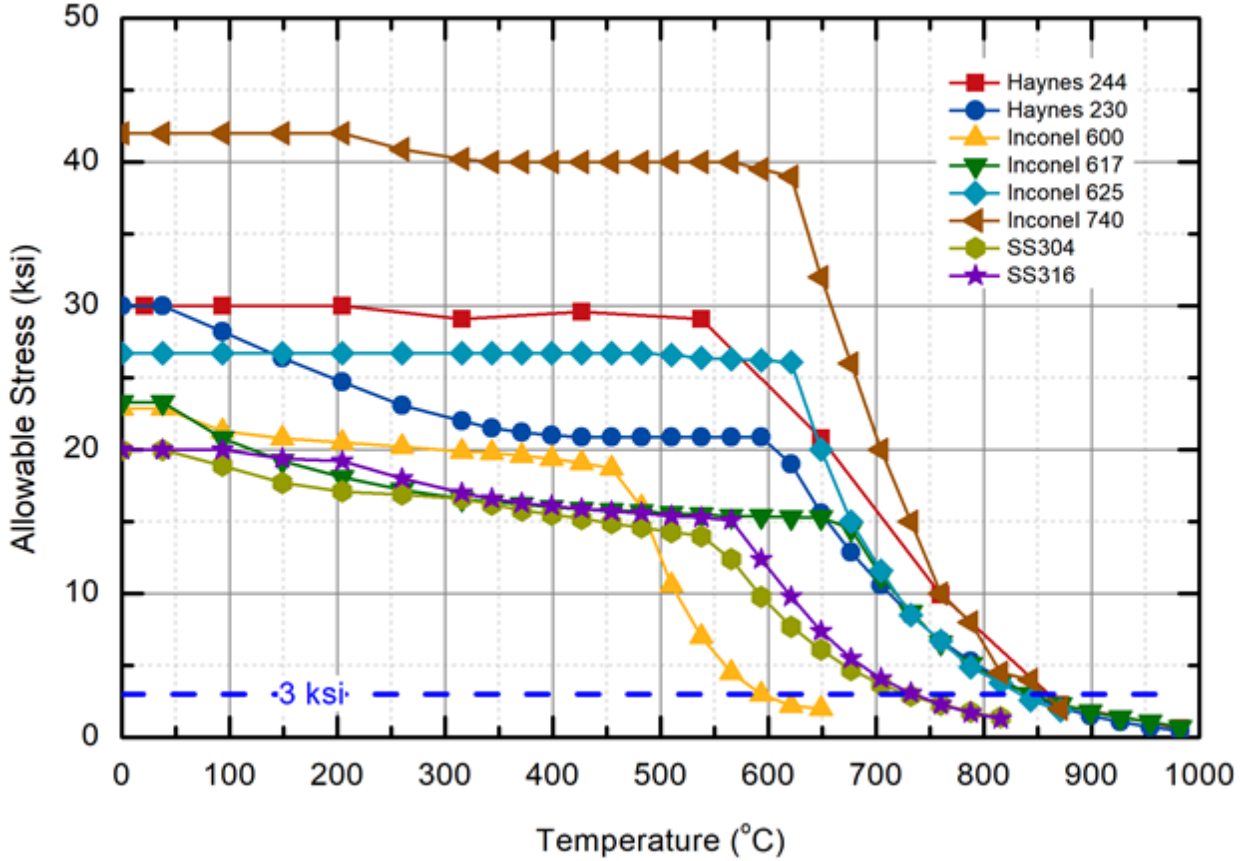
FEA Modeling: Hot Seal Forming Process

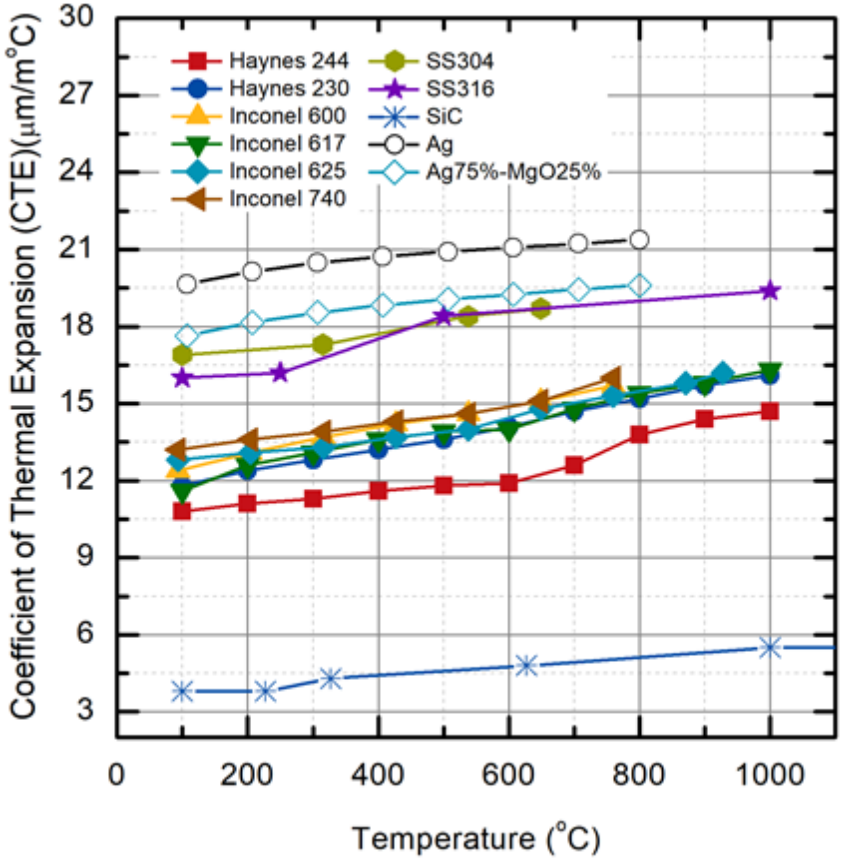
- Developed FEA model of full seal assembly
- Using FEA model to evaluate influence of:
  - Temperature
  - Pressure
  - Ag vs. AgPd U-Ring, ink, and cermet
  - Geometric design optimization (part dimensions, radii, tolerances, etc.)
  - Metal alloy
  - Other design concepts



Improvements for Higher Temperature Seals

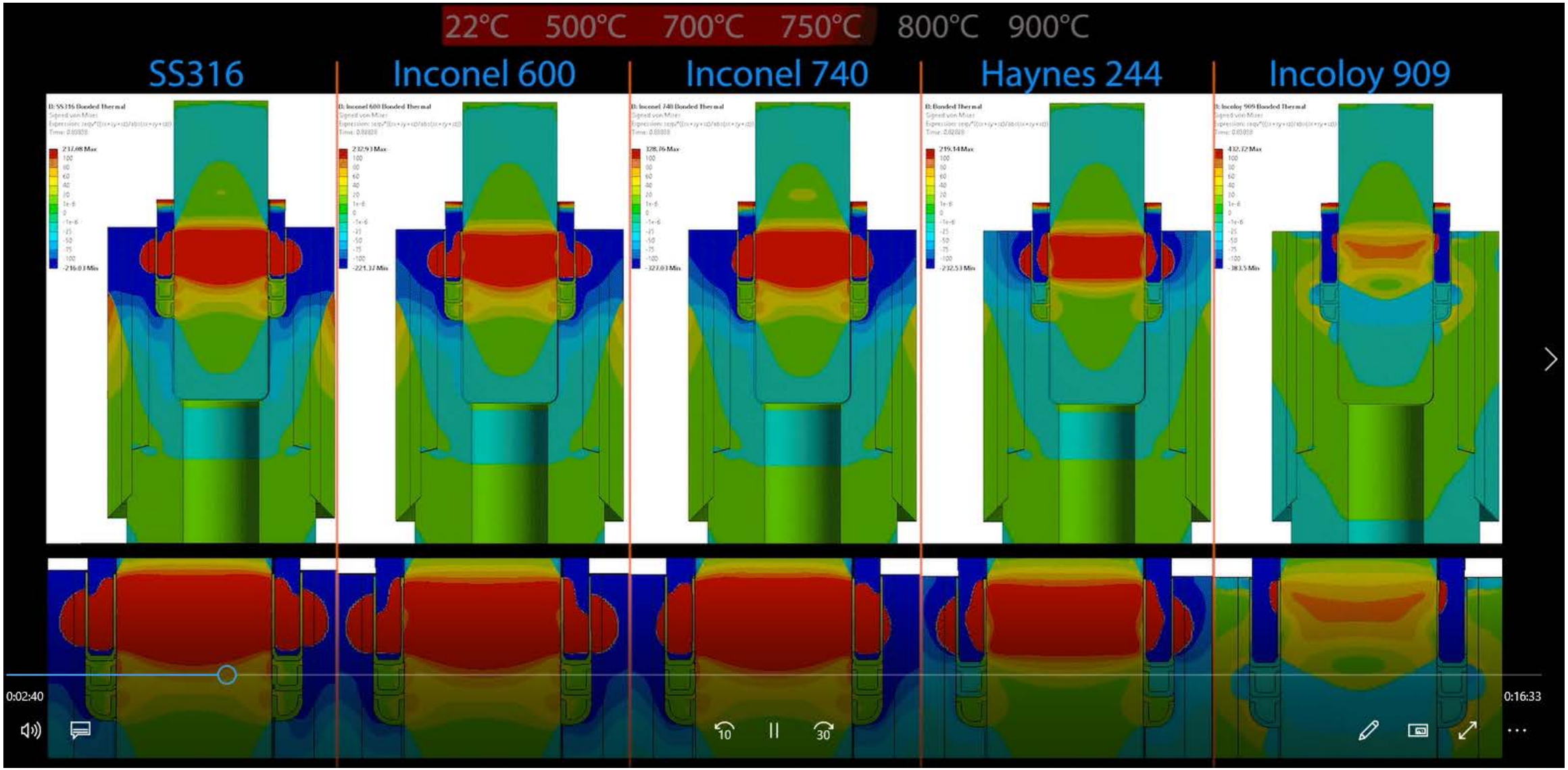
- Allowable stress and CTE for high-temperature metal tubing narrows materials selection
- Use FEA models to optimize design and process reducing testing time and cost
- Verify machining tolerances
- Use XRCT to confirm baseline seal assemblies



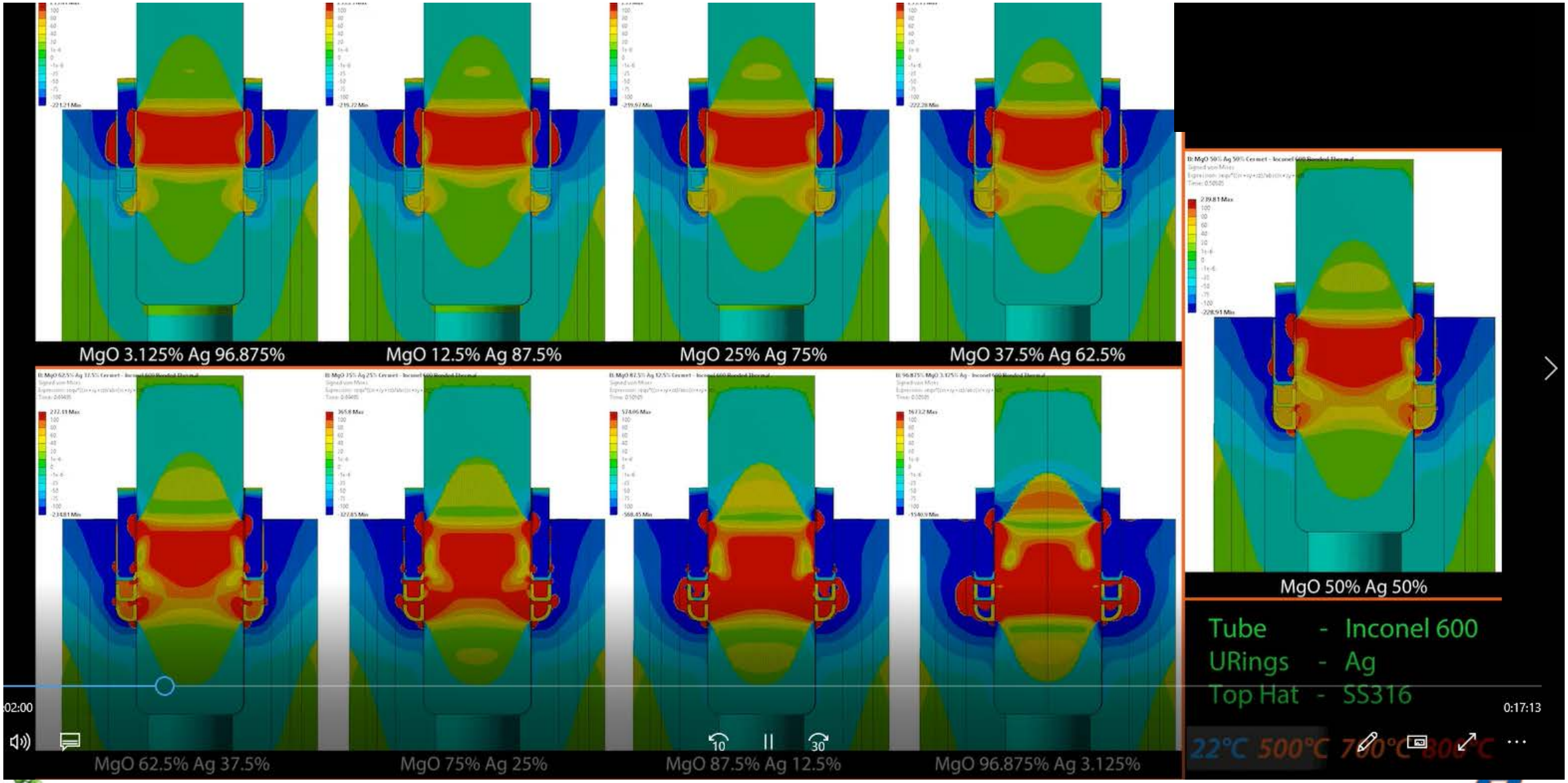


[1] ASME, ASME Boiler and Pressure Vessel Code: Section II Part D. New York, NY: ASME, 2015.
[2] Allowable stress and CTE were calculated from "Haynes 244 Alloy," Haynes International, Kokomo, IN, 2018.
[3] Boise State University measured the CTE of SiC, Ag, and Ag75%-MgO25%.

FEA Modeling: Influence of Tube Alloy and T

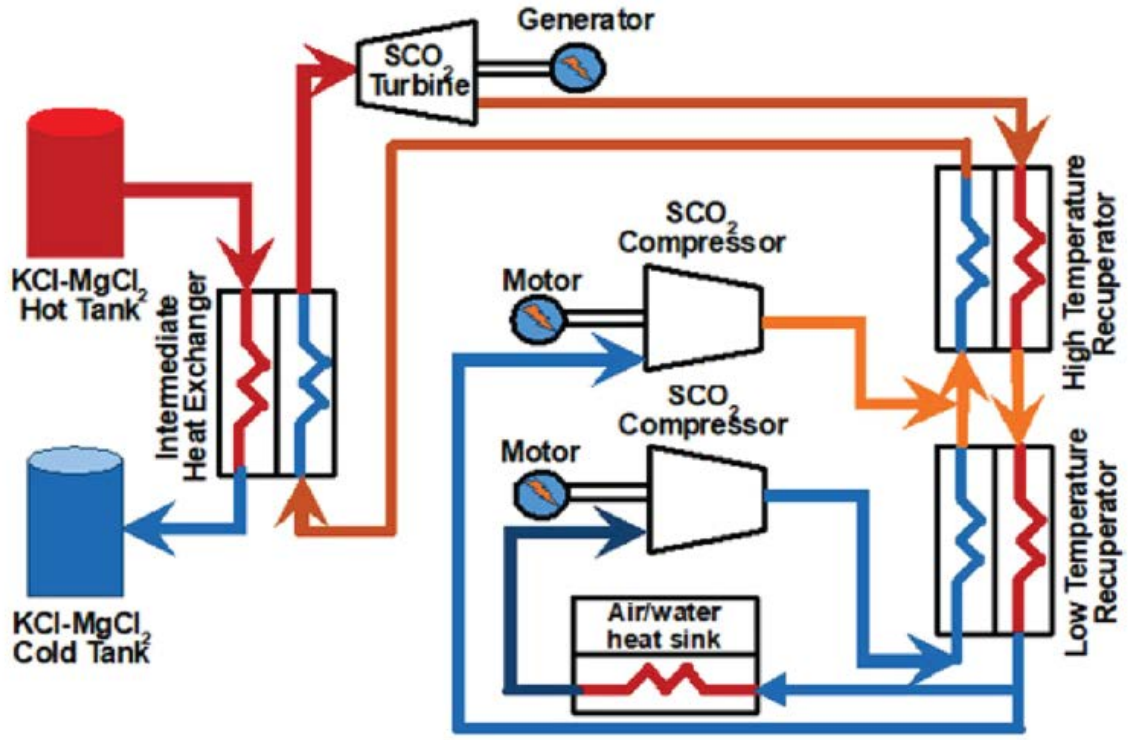


FEA Modeling: Influence of Cermet Composition and T



Voice of Customer (VOC) Inputs

- Need voice of customer (VOC) inputs to establish next demonstration prototype seal design
  1) Identify end users
  2) Identify applications
  3) Maximum seal temperature
  4) Maximum seal pressure
  5) Pressurization direction
  6) No. of thermal cycles
  7) Permissible leak rate
  8) Heat transfer fluids
  9) Tube size and material
  10) Heat exchanger type, material, and flows
  11) Access, footprint, logistics
  12) Cost



- Leverage high P and high T capabilities at DOE labs and/or potential commercialization partners for abuse/reliability testing of baseline and prototype seal designs

Caccia, M., et al. "Ceramic–metal composites for heat exchangers in concentrated solar power plants." Nature 562, no. 7727 (2018): 406.

Summary

- Cermet-filled U-Ring seal design has demonstrated good performance
  - IN600/**Ag**/SiC seal at 3000 psi and **700 °C**
  - IN600/**AgPd**/SiC seal 3000 psi and **750 °C**
- IN600/AgPd/SiC seal failed after 1st thermal cycle to 800 °C
- May be related to fundamental material properties of metal tubing
- Evaluating the use of more exotic alloys to extend seal temperature limit
- Established XRCT capability in collaboration with INL for NDE of seal assemblies
- Initiated failure analysis (FA) plans to identify root cause(s), corrective action(s), and refine seal design and forming process
  - XRCT NDE
  - Destructive cross-sections, SEM/EDS
  - FEA coupled with XRCT and FA for supporting forming process improvements
- Initiated efforts to get VOC requirements

Future Efforts

- Fabricate and test more Ag alloy-based seals
- Continue to perform detailed failure analysis on failed and baseline seals
- Continue to use FEA and FA coupled with experiment results to optimize hot seal forming conditions for Ag Alloy U-Rings, paste, and cermet
- Continue cermet characterization and diffusion bonding first principles studies in parallel and incorporate results as appropriate
- Obtain VOC inputs for high T seal applications for advanced power generation: seal operating conditions, fluids, T, P, dimensions
- Leverage VOC inputs to identify applications that may be able to use existing and improved seal designs
- Use FEA and FA tools to develop new designs that may be able to overcome the metal tubing temperature limitations
- Benchmark high P and high T testing capabilities at DOE labs and/or potential commercialization partners